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Rates of shoreline change along the coast of Bangladesh

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Abstract

Bangladesh, at the confluence of the sediment-laden Ganges and Brahmaputra Rivers, supports an enormous and rapidly growing population (>140 million in 2011), across low-lying alluvial and delta plains that have accumulated over the past few thousand years. It has been identified as one of the most vulnerable places in the world to the impacts of climate change and sea-level rise. Although abundant sediment supply has resulted in accretion on some parts of the coast of Bangladesh, others are experiencing rapid erosion. We report a systematic assessment of rates of shoreline change over a 20-year period from 1989 to 2009, using Landsat satellite images with pixel resolution of 30 m on the ground. A Band ratio approach, using Band-5 divided by Band-2, discriminated the water line on images that were largely cloud-free, adequately registered, and at comparable tidal stages. Rates of shoreline change were calculated for >16,000 transects generated at 50 m intervals along the entire mainland coastline (>1,100 km) and major islands, using the End Point Rate (EPR) method in the Digital Shoreline Analysis System (DSAS) extension in ArcGIS®. Erosion characterises most of the seaward margin of the Sundarbans in western Bangladesh. Retreat rates of up to 20 m/yr are typical, with little evidence that local devastation of the mangrove fringe by Cyclone Sidr in November 2007 had resulted in uncharacteristic long-term rates of retreat where it made landfall. Erosion exceeded accretion in the Barguna Patuakhali coastal zone, most of which eroded at up to 20 m/yr, but with truncation of the southern tip of the Patharghata Upazila at up to 100 m/yr. In Bhola, erosion at rates of up to 120 m/yr were observed along much of the coast, but in the Noakhali Feni coastal zone, similar rates of erosion were balanced by rapid accretion of the main promontory by more than 600 m/yr. Rates of change were more subdued in the Chittagong and Cox's Bazar coastal zones of southeast Bangladesh. Islands in the Meghna estuary were especially dynamic; Hatiya Island accreted along some of its shoreline by 50 km2 between 1989 and 2009, but lost 65 km2 through erosion elsewhere, resulting in the island moving south. Similar trends were observed on adjacent islands. The overall area changed relatively little across the entire coastline over the 20-year period with accretion of up to 315 km2, countered by erosion of about 307 km2.

Keywords

shoreline, bangladesh, change, along, rates, coast, GeoQuest

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Abstract

Bangladesh, at the confluence of the sediment-laden Ganges and Brahmaputra Rivers, supports an enormous and rapidly growing population (>140 million in 2011), across low-lying alluvial and delta plains that have accumulated over the past few thousand years. It has been identified as one of the most vulnerable places in the world to the impacts of climate change and sea-level rise. Although abundant sediment supply has resulted in accretion on some parts of the coast of Bangladesh, others are experiencing rapid erosion. We report a systematic assessment of rates of shoreline change over a 20-year period from 1989 to 2009, using Landsat satellite images with pixel resolution of 30 m on the ground. A Band ratio approach, using Band-5 divided by Band-2, discriminated the water line on images that were largely cloud-free, adequately registered, and at comparable tidal stages. Rates of shoreline change were calculated for >16,000 transects generated at 50 m intervals along the entire mainland coastline (>1100 km) and major islands, using the End Point Rate (EPR) method in the Digital Shoreline Analysis System (DSAS) extension in ArcGIS®. Erosion characterises most of the seaward margin of the Sundarbans in western Bangladesh. Retreat rates of up to 20 m/yr are typical, with little evidence that local devastation of the mangrove fringe by Cyclone Sidr in November 2007 had resulted in uncharacteristic long-term rates of retreat where it made landfall. Erosion exceeded accretion in the Barguna Patuakhali coastal zone, most of which eroded at up to 20 m/yr, but with truncation of the southern tip of the Patharghata Upazila at up to 100 m/yr. In Bhola, erosion at rates of up to 120 m/yr were observed along much of the coast, but in the Noakhali Feni coastal zone, similar rates of erosion were balanced by rapid accretion of the main promontory by more than 600 m/yr. Rates of change were more subdued in the Chittagong and Cox's Bazar coastal zones of southeast Bangladesh. Islands in the Meghna estuary were especially dynamic; Hatiya Island accreted along some of its shoreline by 50 km^2 between 1989 and 2009, but lost 65 km^2 through erosion elsewhere, resulting in the island moving south. Similar trends were observed on adjacent islands. The overall area changed relatively little across the entire coastline over the 20-year period with accretion of up to 315 km^2, countered by erosion of about 307 km^2.

Keywords Shoreline change · Landsat imagery · delta · Sundarbans · Bay of Bengal · Bangladesh

Introduction

Bangladesh lies at the mouth of two of the largest rivers in the world, the Ganges and Brahmaputra, draining from the Himalayan massif. Most of the country is part of the Bengal Basin, one of the most extensive geosynclines in the world. It has a large, and rapidly growing population (142.3 million in 2011 (BBS 2011) and forecast to be 169 million by 2021 (UNFPA 2011)), much of which is exposed to extensive flooding as the rivers overtop their banks during the monsoon season. Most of the population live on the low-lying floodplains or delta plains; more than 129 million people are considered to be living on the Holocene delta plain of the Ganges-Brahmaputra Rivers, including a proportion that is West Bengal in India (Woodroffe et al. 2006). As a consequence, Bangladesh is considered one of the most vulnerable countries in the world to the impacts of climate change, particularly sea-level rise and storm-surge intensification (Warrick and Ahmad 1996, Cruz et al. 2007, Nicholls et al. 2007; Sarwar and Khan 2007, Karim and Mimura 2008).

The coastal zone of Bangladesh covers an area of 47,201 km^2 (WARPO 2006). This area provides shelter, sustenance and livelihood for approximately 46 million people, with 2.85 million hectares of cultivable land (Bala and Hossain, 2010) supporting 20% of the rice production of Bangladesh (Begum and Fleming 1997). In addition to the resources provided by the coastal zone of Bangladesh, the region is also critical because it contains the world's largest mangrove forest, the Sundarbans, which has been set aside for conservation.

The Ganges River drains a catchment of 1,114,000 km^2 and the Brahmaputra River a catchment of 935,000 km^2, supplying in combination around a billion tonnes of sediment each year to the Bengal Basin. Delta plains exceed 115,000 km^2 in surface area (Woodroffe et al., 2006), comprising the Meghna Delta plain (built by the two rivers downstream of their confluence) to the east, and an abandoned delta plain, the Gangetic Tidal plain to the west (Fig. 1). Rapid aggradation of sediment occurred from 11,000-7,000 years BP as the combined deltas built seaward, despite the rapid rate of postglacial sea-level rise (Goodbred 2003). Since sea level reached its present level the mouth of the Ganges appears to have occupied a series of positions, avulsing progressively to the east. The high rate of sediment supply results in rapid accretion in parts of the Meghna River estuary, east of the Haringhata River, with sediment accumulation of 3.8×10^7 t/yr (Mikhailov and Dotsenko 2007). Comparing the 1792 Rennel chart, the 1840 survey report on the Sundarbans, Admiralty Charts of 1904 and 1908 and a 1984 Landsat image, a net accretion rate of 7 km^2/yr occurred over the period 1792 to 1984 (Allison, 1998a, b). However, other sections of the coast experience rapid erosion because of strong tidal currents, vigorous wave action and other factors, including the landfall of tropical cyclones. Erosion has been observed along the shoreline of the Sundarbans region (Allison and Kepple 2001). Rapid subsidence, perhaps tectonic but accentuated by compaction and dewatering of sediments, has been inferred for this western, abandoned-delta section of the Bangladesh coast (Hoque and Alam 1997). This has led to increased tidal domination and overall recession of these former distributaries with erosion of the shoreline by 3-4 km since original mapping by James Rennel in1792 (Allison, 1998a, b).

A comparison of Landsat images from 1973 to 2000 indicated little change in the overall extent of mangrove in the Sundarbans (Giri et al. 2007). A recent study using multi-temporal Landsat imagery of the Sundarbans indicated significant variation in erosion and accretion trends from 1973 to 2010, with erosion being highest in the 1973-1979 period (23.2 km^2/yr of land loss), but decreasing thereafter, and averaging only 7.2 km^2/yr over the entire 1973-2010 time frame, resulting in a loss of 415 km^2 (Rahman et al. 2011). This was partially offset by accretion, particularly between 1979 and 1989, averaging 2.4 km^2/yr over the full 37 years (a total land gain of 245 km^2).

Although Bangladesh receives a larger volume of sediment than any other comparable coast anywhere in the world, some sections of its shoreline are experiencing very rapid erosion. In the more heavily populated parts of the coast, embankments have been constructed to protect shorelines, and planting of mangroves and other technologically simple methods of land reclamation are practised. The objective of this paper is to extend the mapping comparison approach of Mikhailov and Dotsenko (2007), and to assess rates of change in a systematic and consistent manner for the entire coast of Bangladesh. We report a comparison of satellite imagery for the period 1989-2009. By this approach we aim to provide a synoptic view of shoreline change for a 20-year time period as a basis for broader assessment of the vulnerability of the coast in the face of climate change and sea-level rise.

Methods

In order to undertake a shoreline change comparison for the coastal zone of Bangladesh, six scenes of Landsat imagery (referred to as LS-1, LS-2, LS-4, LS-5, LS-3, and

LS-6 respectively) were acquired for two different years: 1989 and 2009 from the Earth Explorer database of the USGS (see Table 1). Four scenes (from rows 44 and 45, and path 136 and 137) capture most of the coastal zone in seven spectral bands (Fig. 1). The remaining two scenes (see Fig. 1) provide information on a small section of the coast not covered by the principal images. The 1989 Landsat-5 Thematic Mapper (TM) imagery has an image resolution of 30 m pixel size for six of the seven spectral bands, whereas 2009 Landsat-7 with the improved Enhanced Thematic Mapper (ETM) scanner acquired all seven bands at 30 m resolution with an additional panchromatic band at 15 m resolution.

Although it would be possible to extract shorelines manually from the satellite images (White et al. 1999), adopting an automated shoreline extraction procedure has several advantages in terms of efficiency and consistency in recognising former shoreline positions for complex and dynamic coasts such as Bangladesh. A Band ratio has been shown to be an efficient approach to automated shoreline identification (Alesheikh et al. 2007). In this method, Band-5 of a Landsat image is divided by Band-2 using the *Band Math* tool in ENVI® 4.5, resulting in three classes: water, which is assigned a pixel value of zero (0), land areas in the range 1-127, and highly reflective land areas with pixel values of 127-255. Some researchers have adopted Band 4 for discrimination of shorelines, or a combination of bands; for example, Benny (1980) used band 7 of the Landsat MSS for shoreline definition, and Marafai et al. (2008) used Band 4 of MSS and Band 5 of ETM for shoreline mapping in Semarang, Indonesia. However, use of Band 5 has been shown to produce up to 96.9% accuracy (Frazier and Page 2000), and was the preferred method adopted in this study.

The simplified band-ratio image was opened in ArcMap® 9.2 and the raster was converted into a vector, and the shoreline (land-water separation) was converted into polylines using the *polygon to line* tool. Small polygons in the land area that probably represented water bodies, such as ponds or small lakes, were eliminated by editing in ArcMap®, and the mouths of rivers and tidal creeks were connected by straight lines to provide a single shoreline for the entire coastal zone. This approach was used to extract the 1989 shoreline from the earlier images and the 2009 shorelines from the more recent images.

Cloud cover obscures many satellite images in this region, and an extensive search of the database was undertaken to use only cloud-free images. The Landsat images obtained from the USGS were pre-registered and projected in WGS84, but the consistency of registration of the 1989 and 2009 images was checked rigorously, using identifiable features, such as road junctions, runways, or bridges, that could be detected on both images. The Sundarbans coastal zone is covered with mangrove forest, and in the absence of visible structures in Landsat images, the junctions of small tidal creeks where checked for registration between the 1989 and 2009 images.

Much of the coast of Bangladesh experiences a large tidal range, reaching up to 6 m or more at Sandwip Island (Barua, 1997). Large errors in shoreline change could result if one image was acquired at low tide and the other at high tide, particularly on an intertidal substrate of gentle gradient as characteristic of much of the Bay of Bengal (Jimenez et al. 1997). In order to minimise such shoreline-change error in the two images, the time of image capture was noted and tidal conditions at that time determined from tidal records held with the Bangladesh Inland Water Transport Authority (BIWTA). Only Landsat images showing good agreement in terms of tidal stage in each of 1989 and 2009 were selected for shoreline analysis.

After identifying the shorelines, the rates of shoreline change along different parts of the coast were calculated using version 4.0 of the Digital Shoreline Analysis System (DSAS) extension in ArcGIS® (Himmelstoss 2009). The End Point Rate (EPR) is the most appropriate of the different statistical approaches available within DSAS for measuring the rate of shoreline change when calculated from only two shoreline positions in time. Shoreline change is calculated relative to a baseline, which can be either a user-defined line or a buffer generated relative to an existing shoreline (Fig. 2). In this study a baseline was inserted manually and transects were created orthogonal to it, at 50 m intervals. A total of 16,499 transects were generated. DSAS calculates the distance of each shoreline from the baseline, and then derives Net Shoreline Movement (NSM) and End Point Rate (EPR), dividing the NSM by the number of intervening years to determine shoreline change in m/yr. Accretion is presented in positive numbers and erosion by a negative number in the DSAS calculation.

Results

Net erosion and accretion rates were calculated for six sections of the mainland coast, and for four of the larger islands, using the same boundaries between the zones for both 1989 and 2009. Particularly rapid accretion, of more than 600 m/yr, was observed in the active mouth of the Meghna estuary, with erosion of up to 285 m/yr on an adjacent island. In the sections below, the major divisions of the Bangladesh shoreline are described.

Sundarbans

Of 2,553 transects examined using DSAS in the Sundarbans coastal zone, to the west of Bangladesh, shoreline retreated by erosion at 2,252 transects while at the remaining 301 transects, the shoreline has advanced seawards by accretion (Fig. 3). Comparison of shoreline positions was found consistent with the observations by Rahman et al. (2011) who showed pronounced erosion on the southernmost promontories facing the Bay of Bengal, but more irregular patterns of erosion or accretion along the margins of the tidal channels within the Sundarbans of both West Bengal and Bangladesh. A total of 7 km^2 land area was accreted in the Bangladeshi Sundarbans coastal zone but erosion of >26 km^2, exceeded accretion by about four times. This represents a net change of about >19 km^2 of mangrove forest in 20 years time, implying that the seaward margin of this Sundarbans coast (Fig. 4) has been lost at the rate of about 1 km^2/yr.

Cyclone Sidr made landfall near the mouth of the Passur River in November 2007. It resulted in local destruction of the mangrove fringe (Fig. 5) but does not appear to have resulted in atypically fast retreat of the coast in this section, compared with the general pattern of recession along the open coast of the Bangladeshi Sundarbans, which is up to about 20 m/yr, similar to that shown by Rahman et al. (2011) for West Bengal.

The distribution of accretion was more irregular than that of erosion, with a prominent infill of mudflats at the site showing the most rapid accretion on the island called Dublarchar (in the centre of Fig. 3). This site existed as a small embayment in the 1989 image, but accumulation of muds at the mouth of two tidal creeks was already apparent, and these have been colonised by vegetation, particularly mangroves, enabling accretion of up to 100 m/yr. The area of Dublarchar island in 1989 and 2009 was 71.6 km^2 and 71.9 km^2 respectively; in spite of rapid accretion recorded on the west of the island.

Bhola, Barguna Patuakhali and Noakhali Feni coastal zones

A similar trend was observed in the Barguna Patuakhali coastal zone to that in the Sundarbans, whereas the Bhola and Noakhali Feni coastal zones, closer to the active river mouths, increasingly showed the influence of the rivers. These latter regions experienced extensive river/estuary bank erosion, but local accretion in a downriver direction in Noakhali

Feni was recorded on the promontory between the estuary of the Feni River and that of the main rivers, where the most rapid rates of accretion exceeded 600 m/yr.

In the Barguna Patuakhali coastal zone, the shoreline at 1,166 transects out of 1,547 was eroding and at 380 transects was accreting with the shoreline at only one transect showing a stable condition (no discernible change at the ±30 m resolution of the imagery). The southern tip of Patharghata Upazila has experienced spectacular erosion, with retreat of almost 100 m/yr between 1989 and 2009, truncating the pattern of tidal creeks. The zone had an accretion of 5.4 km^2, but its erosion was 27.6 km^2, resulting in a net land loss of >22 km^2 along the coast (Fig. 4), which corresponds to >1 km^2/yr. The area of the Patharghata Upazila was reduced by 14.0 km^2 so that its total area became 232. 7 km^2 in 2009.

The Bhola coastal zone was the section of mainland coast that showed the most widespread erosion. The shoreline was eroding at 1,287 transects (with a net land loss of more than 65 km^2) compared with accreting shoreline at only 189 transects, on two sections totalling a length of <14 km of shoreline (and with one stable transect). A length of almost 40 km in the northern part, within the Meghna River estuary was found as one of the most continuous rapidly eroding parts of the entire coastal zone (Fig. 4).

The Noakhali Feni coastal zone was the most dynamic part of the entire shoreline of Bangladesh, showing erosion rates of up to116.7 m/yr and accretion rates of up to 633.1 m/yr, respectively (Fig. 4). About half of the total accretion occurs here, with erosion of 42.9 km^2 in 20 years completely overwhelmed by accretion of 149.9 km^2. The land area of the zone increased about 107 km^2 in just 20 years. Although erosion occurred on the banks of both the Meghna River estuary and the Feni River estuary that enters the Bay of Bengal at its very easternmost, the central peninsula between these was the most rapidly growing section of coastline in the country.

Southeast Bangladesh

The southeast of Bangladesh consists of Chittagong and Cox’s Bazar coastal zones, both on a relatively rugged coast backed by uplands. The Chittagong coastal zone showed more erosion than accretion; erosion and accretion of the shoreline were observed at 1,246 and 767 transects respectively. The rate of erosion was much more subdued. The highest erosion rate observed was 36.5 m/yr and that of accretion was 63.4 m/yr, with the area change analysis showing 12.6 km^2 and 17.1 km^2, respectively. This resulted in a net total increase of 4.5 km^2 land area (Fig. 4).

The coastal zone of Cox's Bazar was the least eroded among the six mainland coastal sections. It showed an erosion of 10.0 km^2 and an accretion of 37.6 km^2, with erosion at 1,253 transects compared to accretion at 1,455 transects (Fig. 4). One rapidly accreting spot in the coastal zone was identified along the shoreline of Moheshkhali. A total area of 33.32 km^2 was accreted along about 16 km length of shoreline. The southernmost tip of the country, the Teknaf peninsula, showed erosion that resulted in a decrease in the total length of the mainland of the country by 2.4 km.

Islands

Hatiya Island was typical of the rapidly changing islands that form and undergo erosion in the Meghna estuary. Hatiya has experienced rapid erosion at its northern end, having retreated at more than 200 m/yr at its fastest (with the most rapidly eroding transect in the country showing >285 m/yr), gouged by the flood flows of the river. However, it has seen net accretion around most of its southern margin, resulting in the island gradually translating its position southwards. Between 1989 and 2009, the island accreted 50.9 km^2 and eroded 65.9 km^2, losing a net land area of almost 15 km^2 (Fig. 4). Out of 1,894 transects, the shoreline was accreting at a total of 739 whereas 1,155 transects were eroding.

The adjacent island of Manpura was eroding very fast; a total of >20 km^2 area of the island disappeared between 1989 and 2009 (Fig. 4). The shoreline was accreting at 129 transects out of 1,297 at an average rate of 3.5 m/yr per transect. Maximum accretion on the island was recorded as 14.3 m/yr that yielded a total accretion of 0.45 km^2 in 20 years. On the other hand, a total of 1,168 transects showed erosion at an average rate of 15.0 m/yr per transect, with the highest rate being 119.6 m/yr.

Sandwip Island was a particularly dynamic char in the mouth of the Meghna River estuary that showed rapid accretion rates as high as 201.6 m/yr. However, the length of eroding and accreting shorelines were nearly balanced. Out of 1,119 transects used in the DSAS analysis, the shoreline was accreting at 590 transects and 529 transects were eroding. After balancing the erosion of 30.1 km^2 by accretion of 42.4 km^2, the island gained a land area of 12.3 km^2 (Fig. 4). The area of the island in 1989 was 231.9 km^2 and that increased to

244.2 km^2 in 2009, and the island has actually become longer with accretion on both its northern and southern tips.

Kutubdia Island eroded faster than it accreted (Fig. 4), and the highest erosion rate was tenfold that of the highest accretion rate. The area of the island was 72.9 km^2 in 1989, but was reduced to 68.7 km^2 in 2009. Out of 863 transects, the shoreline at 462 was eroding, primarily in the southernmost part. The eastern side of the island was almost stable. Erosion and accretion in Kutubdia Island were found to be 5.1 km^2 and 0.9 km^2 respectively. The island showed a net land loss of 4.2 km^2, mostly on its southern part.

There are numerous other smaller islands, and the rapidly changing ‘chars’ are a key feature of the active estuarine setting of the Meghna estuary. Their general pattern of change is probably very similar to that described for the larger islands which have been mapped in detail.

Discussion

The shoreline of the coastal zone of Bangladesh has been changing rapidly (Table 2). Accretion rates as high as 633 m/yr were observed in the Noakhali coastal area. Erosion rates of up to 285 m/yr were obtained on Hatiya Island. Out of all the 16,499 transects, the shoreline at 5,480 transects showed accretion and that at 11,002 showed erosion; only 17 transects were in a stable condition at the limit of change detection which was of the order of ±30 m in 20 years. This implies that the length of eroding shoreline was more than twice that of accreting shorelines, although the highest accretion rate was more than the twice that of the highest erosion rate.

Despite rapid erosion and accretion, the total land area of the coastal zone changed very little (a net land gain of 8.66 km^2). Overall accretion of the coast was 315.5 km^2 and erosion was 306.8 km^2. Generally, the west coast, including the Sundarbans was experiencing erosion, and the east coast was stable, with accretion along the estuary margins in the active Meghna estuary. Islands within the Meghna River estuary showed varying trends. The islands of Manpura, Hatiya and Kutubdia were eroding while Sandwip was accreting. Although Hatiya Island recorded the highest erosion rate of any site, the second and the third highest accretion rates were also recorded on Hatiya and Sandwip Islands. Maximum accretion on Hatiya and Sandwip Islands was 221.9 m/yr and 201.6 m/yr respectively. In contrast, the highest accretion on the other two islands was very low. On Manpura Island, the highest accretion rate was 14.3 m/yr and on Kutubdia Island it was only 11.6 m/yr. Other parts of the coastal zone showed maximum accretion rates of <200 m/yr. The Cox's Bazar coastal zone showed a maximum accretion rate of 198.1 m/yr, compared with accretion of 107.7 m/yr in the Sundarbans coastal zone. Maximum accretion rates in the Barguna Patuakhali coastal zone, Chittagong coastal zone and Bhola coastal zone were up to 77.9 m/yr, 63.4 m/yr and 53.3 m/yr, respectively (Fig. 4). Erosion was also highest on the Meghna islands. Following the highest rate of 285.9 m/yr on Hatiya Island, the second highest erosion rate was 160.0 m/yr on Sandwip Island, which was followed by 124 m/yr along the Bhola coastal zone, 119 m/yr on Manpura Island, and 116 m/yr in the Noakhali Feni coastal zone. The rest of the coastal zone experienced erosion rates less than 100 m/yr. The highest erosion rates on Kutubdia Island, the Barguna Patuakhali coastal zone, Cox's Bazar coastal zone and the Chittagong coastal zone were 98 m/yr, 77 m/yr, 51 m/yr and 36 m/yr respectively.

The total length of the shoreline of Bangladesh in 1989 and 2009 was 1139.9 km and 1180.9 km, respectively, although it is important to note that shoreline length is scale dependent, increasing with the detail (scale) at which it is mapped. The analysis shows some interesting changes in the length of the coast, implying a total increase of 40.9 km in only 20 years. On average, the shoreline of the mainland increased by 2.62% in 20 years (an increase of 21.5 km, from 823.7 km in 1989 to 845.2 km in 2009). The shoreline length of Hatiya and Sandwip Islands increased 12.5% and 20.2% respectively in 20 years, whereas, the shorelines of Manpura and Kutubdia Islands decreased by 9.46% and 5.65% in the same time frame (Table 3).

Figure 4a summarises the geographical pattern of erosion and accretion. It indicates that the sections of coast that have undergone the most rapid accretion are on the downstream ends of the promontory separating the Feni and Meghna Rivers, or on nearby islands. Net erosion occurred on river banks in the Meghna estuary, and along the southern margin of the Sundarbans and adjacent coasts of the abandoned Ganges delta lobes. The summary by coastal zones (Fig. 4b) reinforces the significance of sedimentation in the Noakhali Feni coastal zone. It also shows the variability in shoreline behaviour on the major islands, a trend which is characteristic of the many smaller islands, many of which are called 'chars', a term that refers to recently deposited land.

The coast along the Meghna River estuary is very dynamic with rapid erosion and accretion. The Ganges-Brahmaputra system carries about 1 billion tonnes of sediment each year (Allison 1998a, Islam et al. 1999). About 30% of the modern sediment is distributed in the delta plain (Goodbred and Kuehl 1998), 21% along the topset of the subaqueous delta (Allison 1998b), 20% along the foreset of the subaqueous delta (Michels et al. 1998) and the rest 29% is carried to the Swatch of No Ground (Goodbred and Kuehl 1999). These huge supplies of sediment contribute to the rapid accretion along the coastal zone, especially in the Meghna River Estuary area. The rate of accretion on the eastern coast of the Meghna River estuary is high, creating new land through the formation of new islands and subsequent merging of smaller ones. However, this pattern of high accretion is not consistent along the coast as significant erosion occurred on the western coast of the Meghna River estuary and along the northern parts of Manpura and Hatiya Islands, perhaps due to the effect of strong river currents Additionally, engineering works, including dam and dyke construction, have reduced downstream water flows and the transport of sediment for deposition, while strong tidal flows may facilitate the transport of sediment away from the coast (Mikhailov and Dotsenko 2007).

The Sundarbans, where Holocene deltaic deposits vary in thickness from 0.5 m to 50 m, may be subsiding at a rate of 2-4 mm/yr (Goodbred and Kuehl 2000a). Similar subsidence is inferred along the southern part of the Indian section of the delta. Despite high suspended sediment in the zone, subsidence and the progressive extension of tidal dominance up the former distributaries of the Ganges are contributing to erosion.

Erosion of the shoreface of the western part of the coastal zone, including the Sundarbans, Barguna Patuakhali and Bhola, is recorded as 103.42 km^2 in the 20-year time frame. This high rate of erosion of >5 km^2/yr is much higher than the estimate by Allison (1998b) who observed an erosion of 1.9 km^2/yr in the western part over the period 1792-1984, implying an acceleration of erosion along the southwest coast. Greater erosion rate has also been observed in a recent study of the adjacent Indian Sundarbans (Rahman et al. 2011). Extensive erosion results from the landfall of tropical cyclones, as shown by the destruction of mangrove, and associated shoreline retreat, in Fig. 5. The observed patterns of shoreline change are likely to continue, or perhaps be exacerbated, with future accelerated sea-level rise.

Substantial changes in shoreline configuration have been reconstructed during the Holocene evolution of this large delta complex (Goodbred and Kuehl 2000b), and paleoshorelines for 3,000 yrs BP, 5,000 ys BP, 7,000 yrs BP and 9,000 yrs BP show little consistency in accretionary or erosional trend as sea level rose to its present level and as the Ganges delta occupied successive lobes from west to east, before occupying the Meghna estuary (Fig. 6). The geomorphological processes associated with the formation of an active delta and its subsequent abandonment and erosion, as along the Gangetic Tidal plain, provide only a first-order indication of likely shoreline trends. The relative sea-level history of Bangladesh during the Holocene remains incompletely understood (Rashid et al. 2013). Current and future sea-level rise is likely to exacerbate erosion that occurs in response to recurring cyclones, strong tidal currents, and gradual subsidence, particularly along the Sundarbans and Barguna Patuakhali coastal zones. However, the dynamics of shoreline change are also influenced by human activities. The rapid accretion rate along the Noakhali coast is likely to be a response to intervention associated with an earthen dam that was built on the Feni River Estuary during the late 1980s (World Bank 1990), as part of what is popularly known as the 'Muhuri Project' to hold freshwater for local irrigation. The Muhuri project has regulated the flow of the Feni River resulting in a reduced flow of water into the Bay of Bengal and subsequent sedimentation. At a more local scale, sediment accretion is enhanced through the construction of embankments and planting of mangroves, and various attempts are made to combat shoreline erosion.

The combination of long-term delta dynamics, episodic extreme storm events, and localised human intervention make it very difficult to determine consistent overall trends in shoreline change, or forecast how particular sections of coast will respond to future climate change. Such an analysis will require other lines of investigation and data. Tidal data available for the Bangladesh coast is incomplete, erroneous and lacking adequate standards in collection, storage and dissemination. Furthermore, subsidence in the coastal zone is not truly understood. The rate of relative sea-level rise is also likely to be locally variable, and a better understanding of this sea-level rise variability would help to depict trends in shoreline change along the delta front. Considering potential threats of future shoreline change, the country will need to develop planning and management strategies for its vast shoreline that consider these rapid rates of change. A protocol recently developed by O'Connor et al. (2010) may be useful as a guideline for sustainable shoreline management.

This study has produced a synoptic overview of rates of shoreline change in the coastal zone over a 20-year period as a basis for a broader assessment of coastal vulnerability that integrates shoreline behaviour with other coastal variables, including geomorphic features, coastal elevation and slope, sea-level rise, tidal range and surge heights. Such information at a broad scale needs to be complemented by more focused local-scale studies that quantify the pattern of change in relation to the needs of communities, and which can form the basis for the formulation of coastal management plans that can provide more holistic management of coastal resources, improving the *ad hoc* efforts of local people who are most at risk.

Conclusions

The coast of Bangladesh is extremely dynamic, almost all of the more than 16,000 transects appeared to have experienced a change in shoreline position in the 20-year period between 1989 and 2009 as extracted from the Landsat images of 30-m spatial resolution. Although the major rivers bring much sediment to the delta, the flows erode the lower river and estuary banks, with only localised deposition in the Noakhali Feni region and in places on the islands. Erosion has been dominant along the seaward margin of the Sundarbans, perhaps augmented by subsidence and the strong tidal flows in this abandoned delta plain.

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Table 1: List of Landsat images used in this study for the coast of Bangladesh.

Image	Resolution	Date	Path	Row	Image no
Landsat TM	30 m	13.02.1989	137	44	LS-1
		05.01.1989	136	44	LS-2
		19.01.1989	138	45	LS-3
		12.01.1989	137	45	LS-4
		05.01.1989	136	45	LS-5
		14.01.1989	135	46	LS-6
Landsat ETM	30 m	05.12.2009	137	44	LS-1
		28.11.2009	136	44	LS-2
		26.11.2009	138	45	LS-3
		05.12.2009	137	45	LS-4
		28.11.2009	136	45	LS-5
		11.04.2009	135	46	LS-6

Table 2: Erosion and accretion along different coastal zone sections between 1989 and 2009

Coastal Zone	Accretion (m/yr)	Erosion (m/yr)	No. of accreting transects	No. of Eroding transects	Transects with no change	Total no of transects
Sundarban coastal zone (SBCZ)	107.68	42.47	301	2252	0	2553
Barguna Patuakhali coastal zone (BPCZ)	77.87	98.26	380	1166	1	1547
Bhola coastal zone (BCZ)	53.3	124.39	189	1287	1	1477
Noakhali Feni coastal zone (NFCZ)	633.14	116.71	528	484	0	1012
Chittagong coastal zone (CCZ)	63.35	36.53	767	1246	0	2013
Cox's Bazaar coastal zone (CBCZ)	198.07	51.83	1455	1253	15	2723
Manpura Is.	14.27	119.35	129	1168	0	1297
Hatia Is.	221.93	285.86	739	1155	0	1894
Sandwip Is.	201.55	160	590	529	0	1119
Kutubdia Is.	11.6	98.04	402	462	0	864
Total	**-**	**-**	**5,480**	**11,002**	**17**	**16,499**

Table 3: Length and change in area along the shoreline of Bangladesh, 1989 to 2009

Shoreline	Length in 1989 (km)	Length in 2009 (km)	Change in shoreline (km)	% change
Shoreline of mainland	823.70	845.24	21.54	2.62
Manpura	73.66	66.69	-6.97	-9.46
Hatiya	128.07	144.15	16.08	12.56
Sandwip	65.04	78.16	13.12	20.17
Kutubdia	49.40	46.61	-2.79	-5.65
Total	**1139.87**	**1180.85**	**40.98**	**3.60**

List of Figures

Fig. 1 Bangladesh showing the Ganges and Brahamputra Rivers (upper) and the coastal zone of Bangladesh, showing the six coastal zone regions (lower): The Sundarbans coastal zone (SBCZ), Barguna Patuakhali coastal zone (BPCZ), Bhola coastal zone (BCZ), Noakhali Feni coastal zone (NFCZ), Chittagong coastal zone (CCZ) and Cox's Bazar coastal zone (CBCZ). Locations referred in the text are numbered: 1). Dublarchar, 2). Patharghata, 3). Manpura Island, 4). Hatiya Island, 5). Sandwip Island, 6). Kutubdia Island, 7), Moheshkhali, 8). Teknaf, 9). The Feni River estuary, 10). The Meghna River estuary. Inset shows the row and path number of the six Landsat scenes covering the coastal zone of Bangladesh.

Fig. 2 Shoreline change assessment procedure using DSAS, involving determination of positions of shorelines in 1989 and 2009 using the band ratio method; manual designation of baseline; generation of transects at 50 m intervals with assignment of unique ID; and intersection of transects and shoreline.

Fig. 3 Shoreline change along the Sundarbans coastal zone, showing the 1989 satellite image (upper), the 2009 image (middle) and the pattern of change at the DSAS transects from west (A) to east (B), where negative rates indicate erosion.

Fig. 4 Overall shoreline change in Bangladesh; a) map showing principal areas of erosion and accretion in the coastal zone; b) summary of erosion and accretion, and net land loss or gain by coastal zone and on the principal islands.

Fig. 5 Devastation of coastal vegetation near the mouth of the Passur River as a consequence of Cyclone Sidr in November 2007. The stumps in the foreground are all that remains of mangrove trees, indicating recession of the shoreline by several tens of metres. A zone of windthrown mixed mangrove trees behind a sandy beach can be seen in the background. (photograph B.G. Jones).

Fig. 6: Paleoshoreline locations inferred during the Holocene for the central and southwestern coasts of Bangladesh (based on Goodbred and Kuehl 2000b).

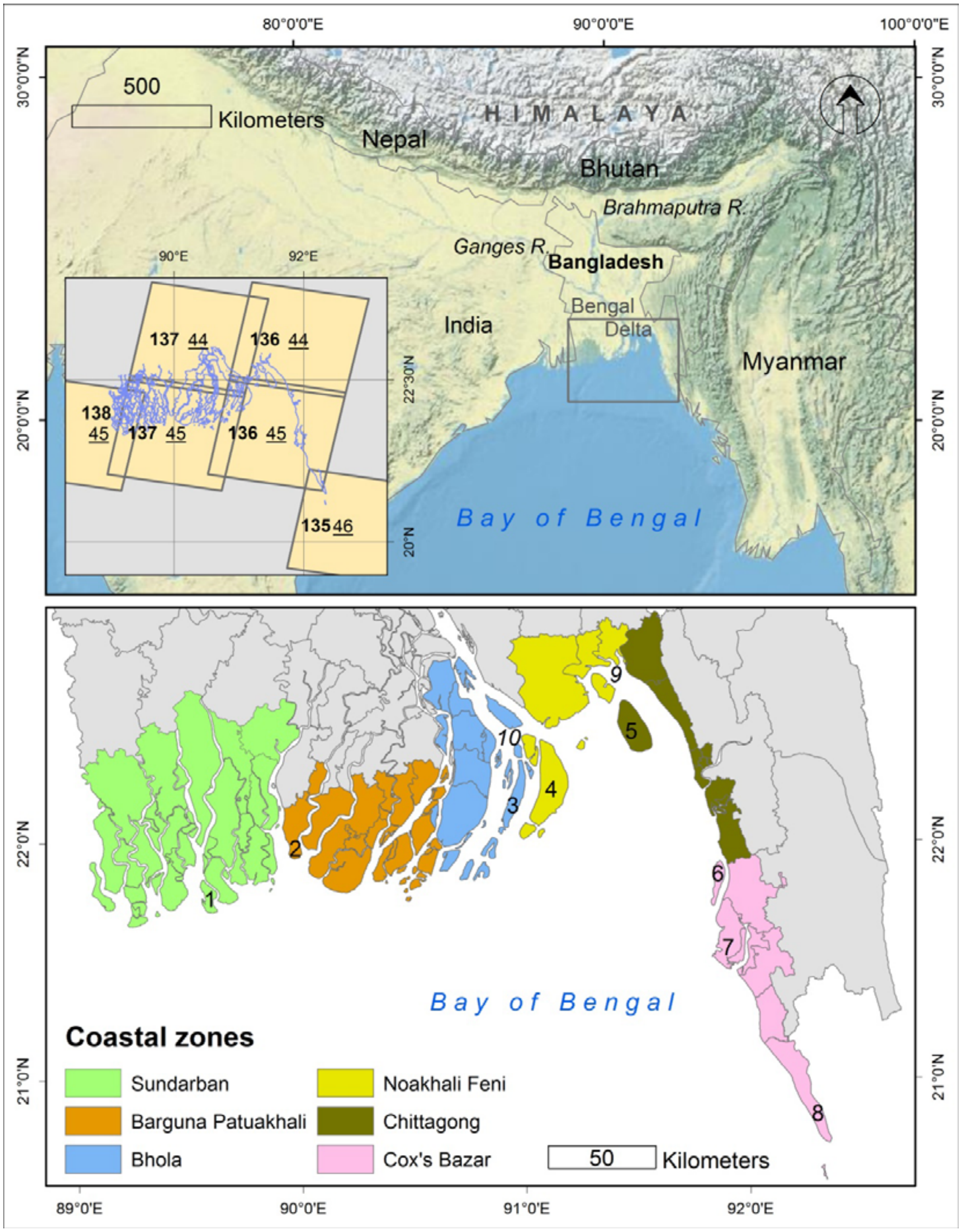

80°0'0"E
90°0'0"E
100°0'0"E
30°0'0"N
20°0'0"N
500
Kilometers
Nepal
HIMALAYA
Bhutan
Brahmaputra R.
Ganges R.
Bangladesh
Bengal
Delta
India
Myanmar
Bay of Bengal
90°E
92°E
22°30'N
20°N
137 44
136 44
138 45
137 45
136 45
135 46
1
2
3
4
5
6
7
8
9
10
Bay of Bengal
Coastal zones
Sundarban
Barguna Patuakhali
Bhola
Noakhali Feni
Chittagong
Cox's Bazar
50
Kilometers
22°0'N
21°0'N
89°0'E
90°0'E
91°0'E
92°0'E

Fig. 1

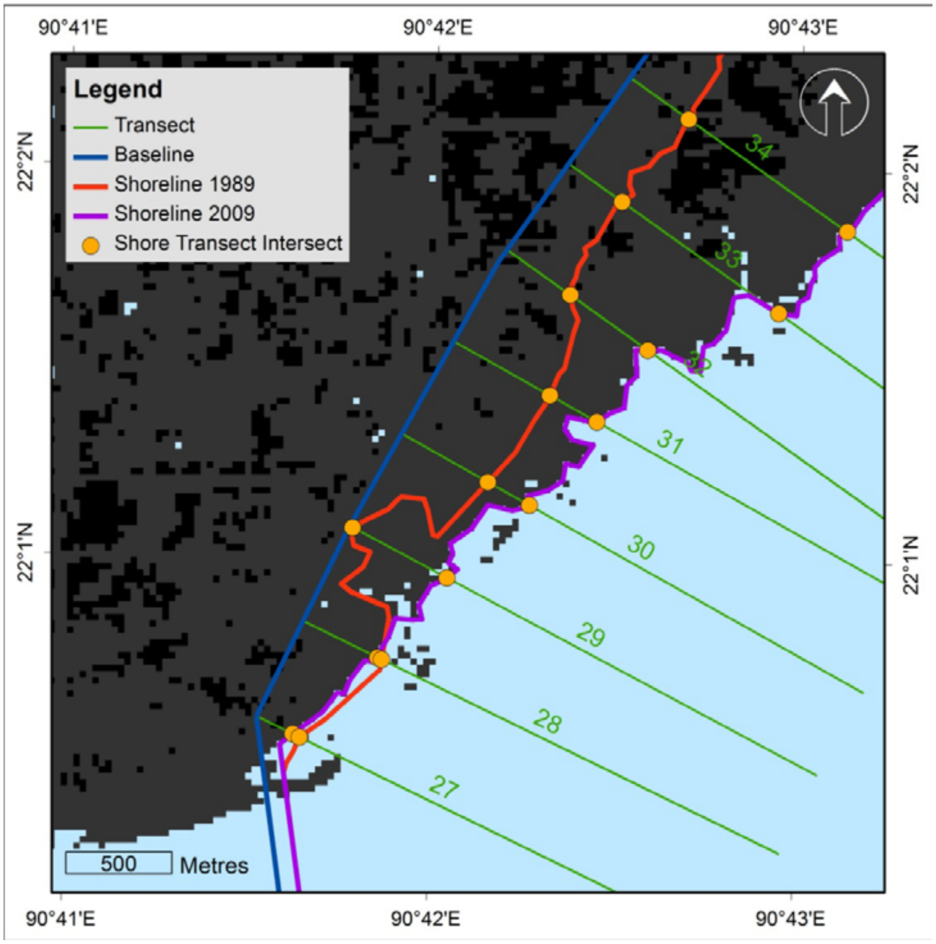

90°41'E
90°42'E
90°43'E
22°2'N
22°1'N
Legend
Transect
Baseline
Shoreline 1989
Shoreline 2009
Shore Transect Intersect
34
33
32
31
30
29
28
27
500 Metres

Fig. 2

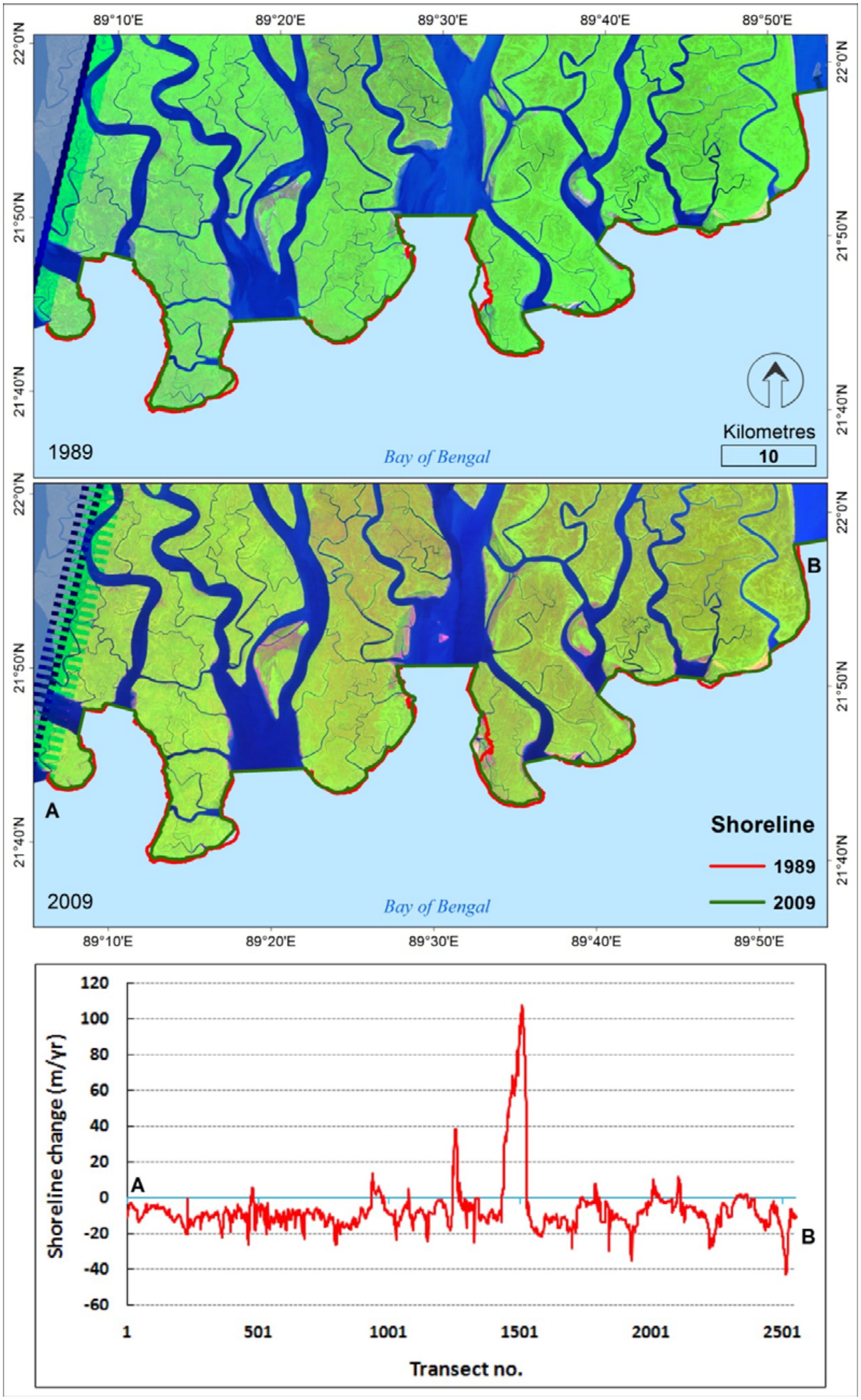
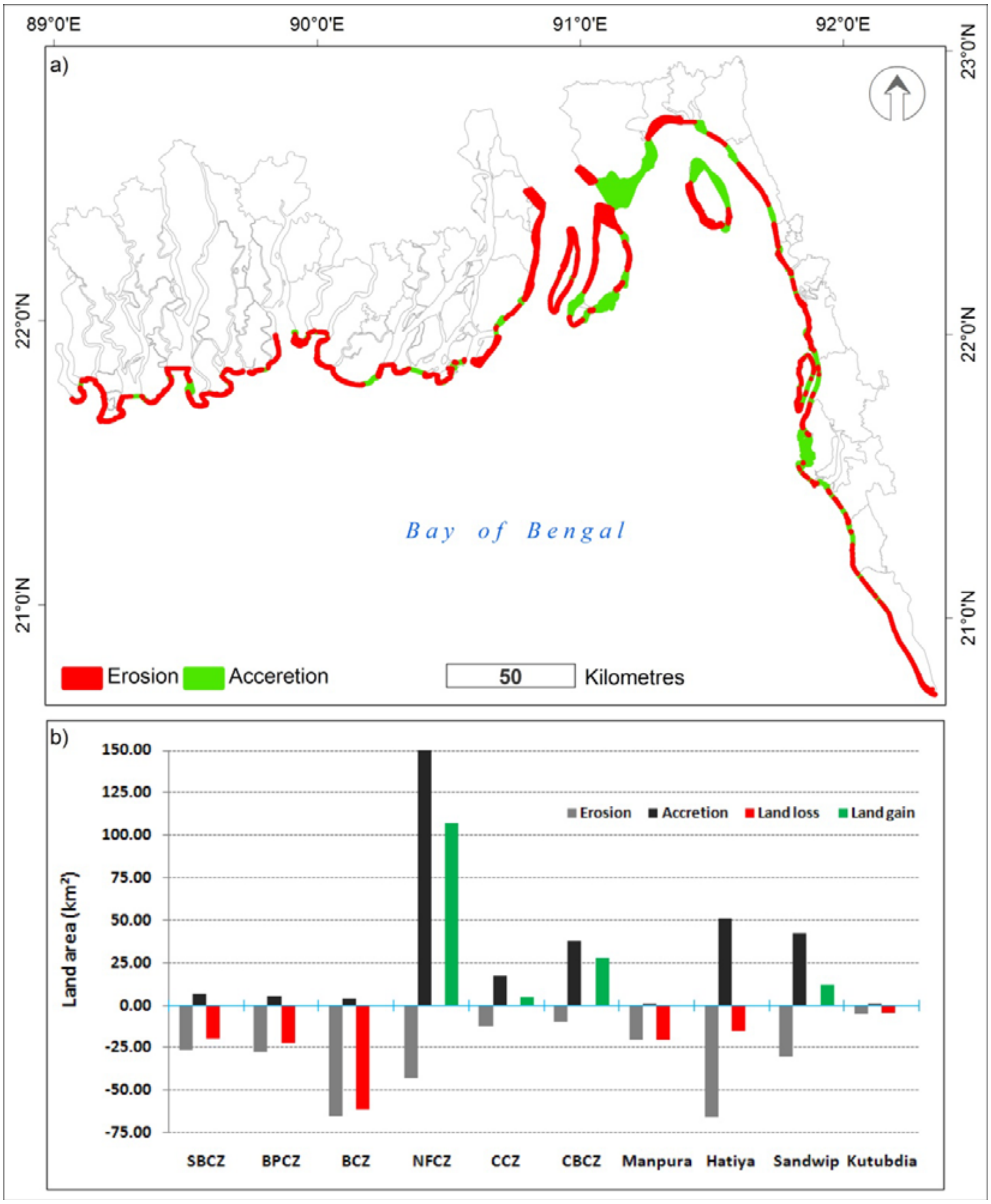

89°10'E
89°20'E
89°30'E
89°40'E
89°50'E
22°0'N
21°50'N
21°40'N
1989
Bay of Bengal
Kilometres
10
2009
A
B
Shoreline
1989
2009
Shoreline change (m/yr)
Transect no.
120
100
80
60
40
20
0
-20
-40
-60
1
501
1001
1501
2001
2501

Fig. 3



89°0'E
90°0'E
91°0'E
92°0'E
23°0'N
22°0'N
21°0'N
a)
Bay of Bengal
Erosion
Acceretion
50
Kilometres
b)
Erosion
Accretion
Land loss
Land gain
Land area (km²)
150.00
125.00
100.00
75.00
50.00
25.00
0.00
-25.00
-50.00
-75.00
SBCZ
BPCZ
BCZ
NFCZ
CCZ
CBCZ
Manpura
Hatiya
Sandwip
Kutubdia

Fig. 4

Fig. 5

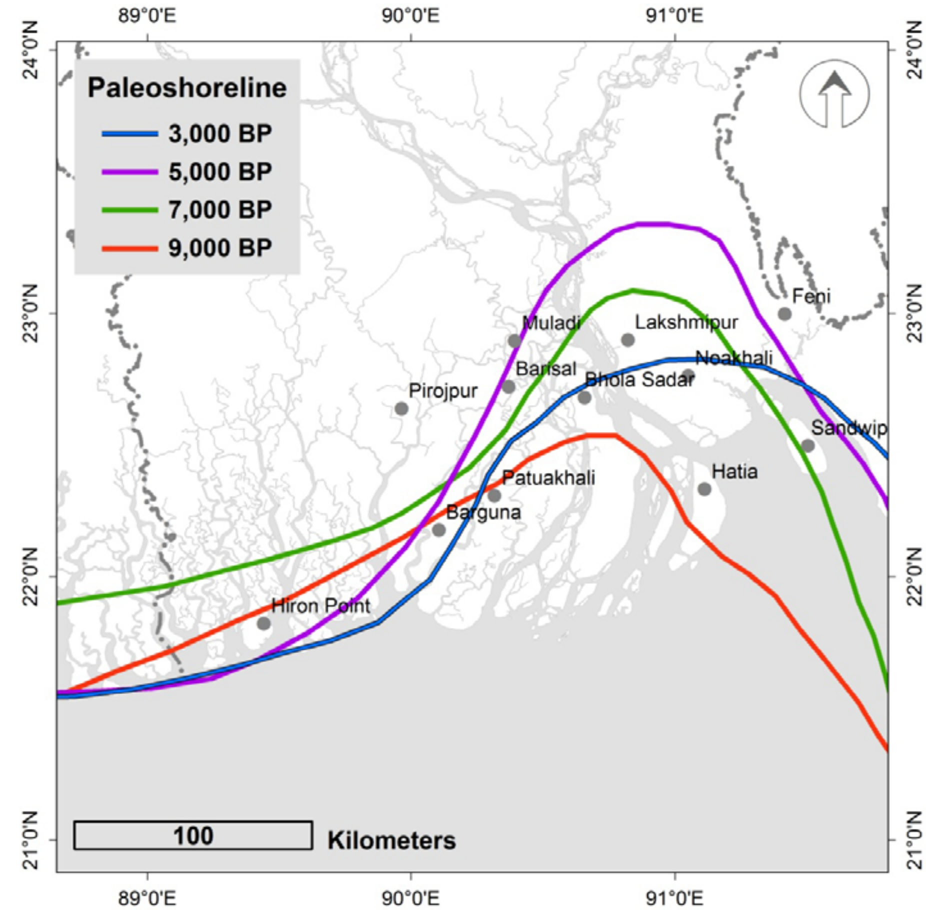

89°0'E
90°0'E
91°0'E
24°0'N
23°0'N
22°0'N
21°0'N
Paleoshoreline
3,000 BP
5,000 BP
7,000 BP
9,000 BP
Feni
Muladi
Lakshmipur
Noakhali
Barisal
Bhola Sadar
Pirojpur
Sandwip
Hatia
Patuakhali
Barguna
Hiron Point
100
Kilometers

Fig. 6